

Cool down of 33.5 Ton Prototype Cryostat

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Scope of calculations/cool down simulations:

Parametrically analyze and study the fluid flow and temperature characteristics of cool-down of the 33.5 Ton prototype cryostat using Computational Fluid Dynamics (CFD) methods. Determine an acceptable way off cooling down the membrane without exceeding the manufacturer's criteria for cool down rate, maximum 15 K/hr from room temperature to 200K and maximum of 10 K/hr below 200K. Attempt to keep a fairly homogeneous temperature gradient in the gas space, as if cooling a TPC and frame.

Cryostat Cooling Method:

Instead of using cold argon gas, the cryostat will be cooled with liquid/gas sprayers. These sprayers will spray liquid argon through the central hole and gaseous argon through the two angled holes. This creates a flat spray pattern of cold argon gas and extra liquid which will evaporate in the fluid volume, creating additional cooling power. Also additional straight gas sprayers will be used to provide momentum and mixing in a more efficient manner, causing the cryostat fluid space to have a relatively steady circulation pattern, and a forced convection dominated type flow. Figure 1 shows one sprayer with water spraying through all orifices.

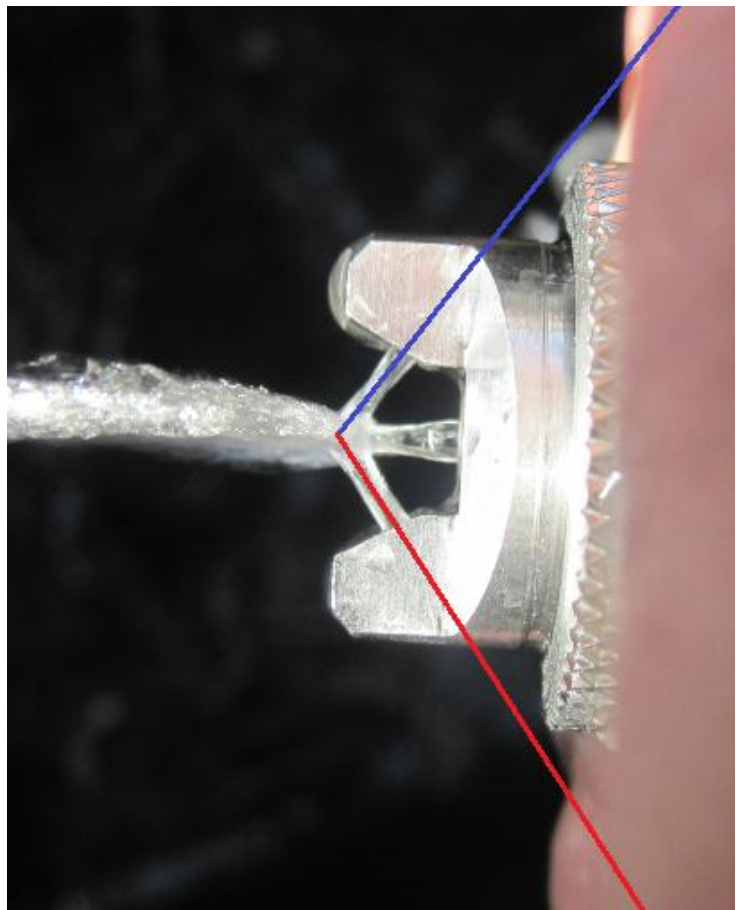


Figure 1: Liquid/gas sprayer spraying water through all orifices.

Model Details:

Materials and Dimensions:

- Cryostat gas space dimensions are 2.7m x 2.7m x 4m
- 304 Stainless steel membrane modeled as 2.5mm thick instead of their actual thickness of 2mm to account for extra material in corrugations
- Fireboard (10mm thick) and Plywood (12mm thick) have nearly identical thermal diffusivity so they were modeled as a single material, (22.5mm) thick with their equivalent average properties.
- 0.3m thick polyurethane insulation.
- Additional Information can found in APPENDIX B (authored by Terry Tope and Mark Adamowski)

3D to 2D conversion:

- Solid materials with locations $0 < y < 2.7$ m (vertical walls between top surface of floor membrane and bottom surface of roof membrane) have the density and thermal conductivity increased by a factor of 2.481 (ratio of perimeter to width of those walls) to account for thermal mass of side walls which are not modeled, while keeping thermal diffusivity, and therefore, transient behavior constant.

Material Properties:

- Argon Gas @ 15.33 psia - all properties temperature dependent and obtained from NIST RefProp. All solid material properties are temperature dependent and obtained from manufacturer specs, NIST cryogenic database, or other relevant sources. More details can be found in APPENDIX A.

Initial conditions:

- Transient model initialized from steady state solution of all materials at 293K, and a steady inflow of argon gas momentum at 293K.

Boundary conditions:

- Rather than actually modeling the two phase evaporation of the liquid/gas sprayers, they were modeled as volumetric source terms applied to a “spray volume” which includes all the equivalent continuity, momentum, and cooling power of the sprayers themselves. These sprayers were near the bottom left corner of the cryostat spraying directly to the right, see APPENDIX B.
- The cryostat contained one outlet on the top.
- Outer insulation walls held at 293K

Parametric Simulation Results:

The cool down was analyzed parametrically by varying the amount of liquid and gas sprayed into the fluid volume. It was found the momentum must be high enough to overcome the buoyant effects of the gas. To simplify everything, the only two parameters which determine the flow/temperature characteristics of the cool down, are the *input momentum* (from the high velocity gas) and *cooling power* (from the liquid). Fortunately, each of these parameters can be controlled separately using the liquid/gas sprayers. The *input momentum* provides the circulation, and this helps keep the gas space at a near homogeneous temperature, causing forced convection and increasing Reynolds number. As the *cooling power* is increased, by consequence, the temperature difference between the gas and the membrane also increases, since it raises the Grashof number. The Richardson number = $Gr/(Re^2)$ describes the dominance of either forced convection or natural convection. If the *cooling power* is increased too much, without increasing the *input momentum*, so increases the temperature gradient at the fluid-solid interface. An increase in this temperature difference raises Grashof and Richardson, which can cause the fluid space to lose its steady circulation pattern since natural convection and buoyancy start to influence the flow. A buoyant flow pattern reduces the spatial homogeneousness of the entire temperature field, and a more stratified gas space temperature is seen. As the Grashof and Reynolds numbers have no universal definition, using the parametric analyses, the length scale was tuned to cause Richardson to become greater than 1 at the onset of natural convection influenced flow. Figure 2 shows the Richardson number with respect to gas space temperature for one simulation, and Figures 3a and 3b show the flow pattern of this same simulation before and after the switch to natural convection influence. An animation of this transient cool down can be seen in the attachment: “*Fluid Flow Switch to Natural Convection.wmv*”, where the onset of natural convection occurs at the end of the simulation, just before it was stopped. The increase of Richardson with decreasing temperature is due to the volume expansion coefficient of a gas increasing with decreasing temperature, since density and temperature are inversely proportional.

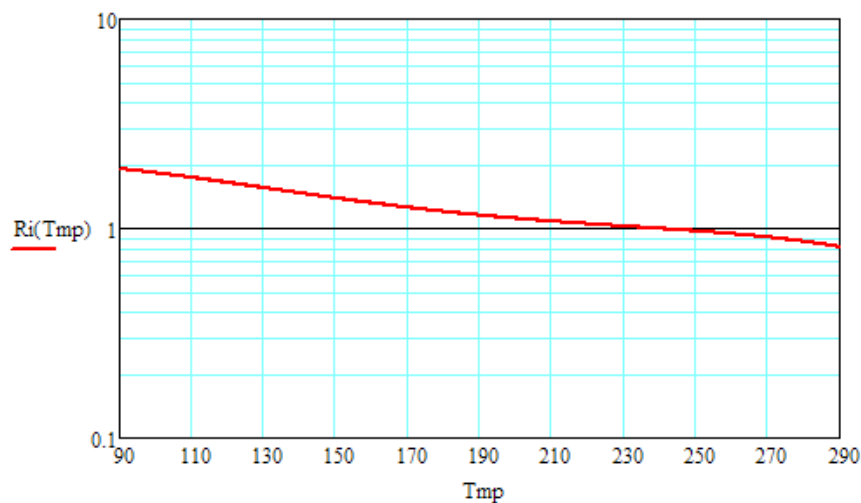


Figure 2: Tuned Richardson number of one simulation with respect to argon gas temperature.

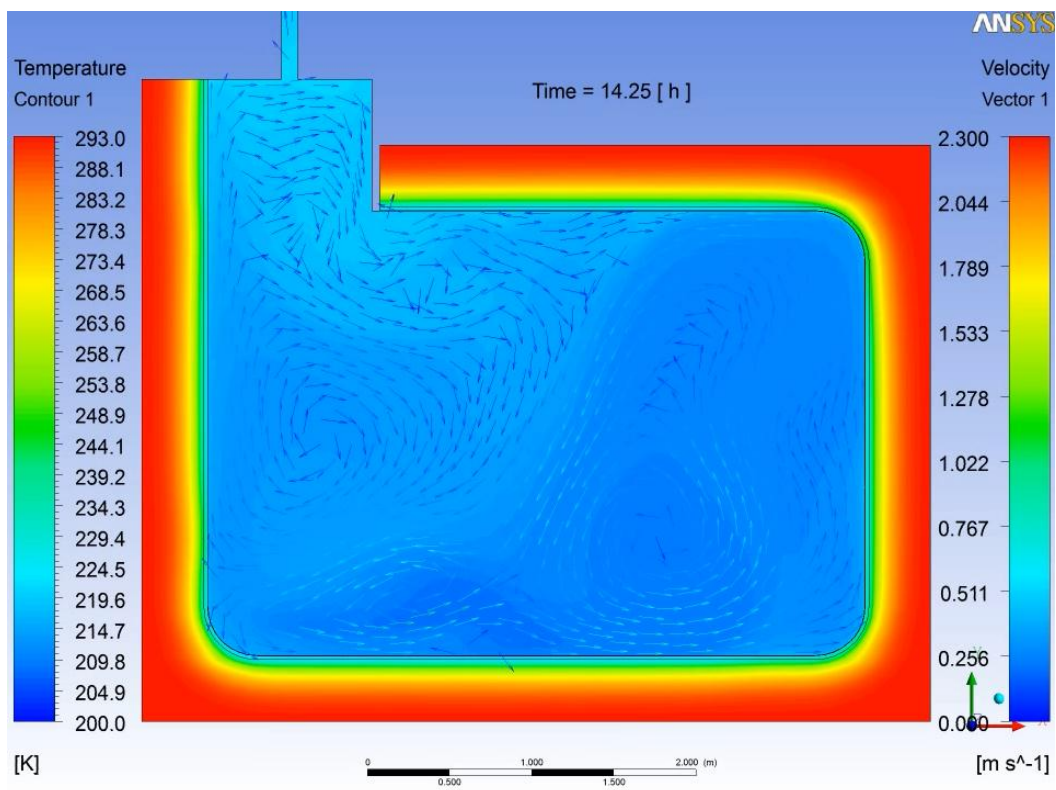
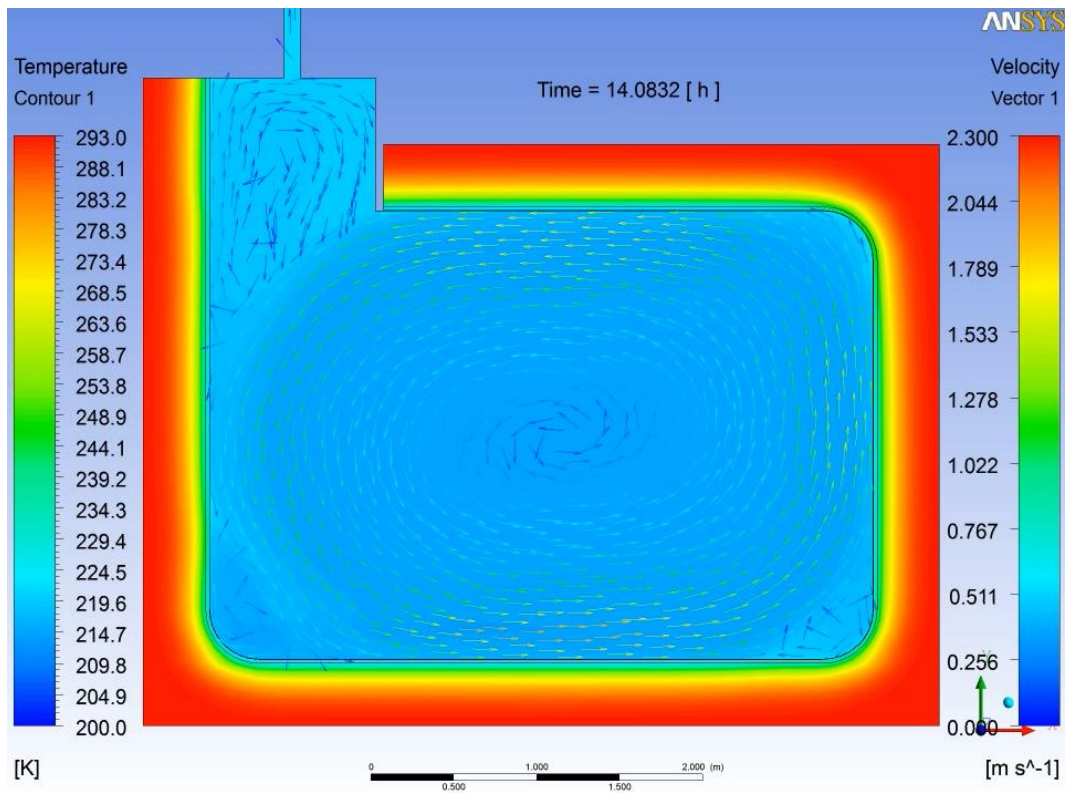


Figure 3: Steady flow pattern becoming influenced by natural convection as Richardson number becomes greater than 1.

Final cooling spray determination:

After thorough research in proper determination of the Richardson number, the amount of liquid and gas from the sprayers was adjusted to keep this value below 1 throughout the cool down, see Figure 4. This resulted in the conclusion that values of the following would suffice to meet all required cooling parameters: (more detail shown in appendix A)

Total Momentum:	3.93 N*s/s
Total Continuity:	36.04 gm/sec (equivalent argon gas as saturated temperature)
Total Energy:	-1241 Watts (from additional cooling of liquid vaporization)

This was achieved by spraying:

Liquid spray:	22.158 gm/sec
Gas spray:	13.881 gm/sec (half of gas through straight nozzles)

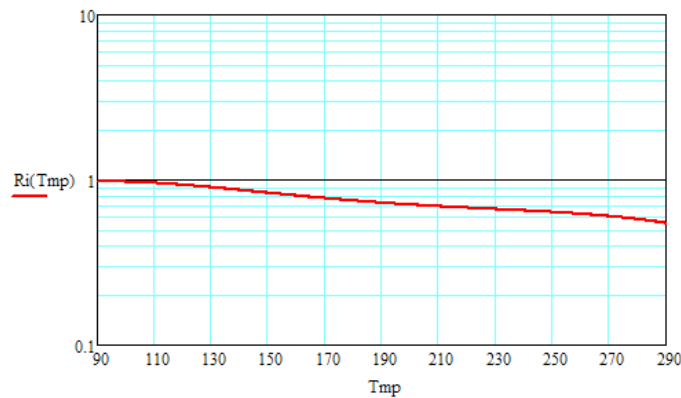


Figure 4: Richardson number of final cooling simulation

Final Cooling Spray Simulation Results:

Cooling Power with respect to gas space temperature is seen in Figure 5. Average temperature of gas space and membrane are shown in Figure 6; the cooling rate of the membrane is shown in Figure 7. An animation of the cool down is shown in the attachment: "Final Cooling Simulation.wmv"

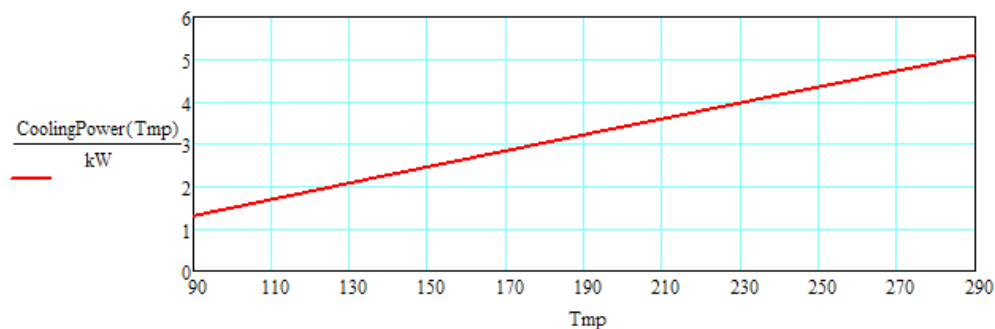


Figure 5: Cooling Power with respect to gas space temperature

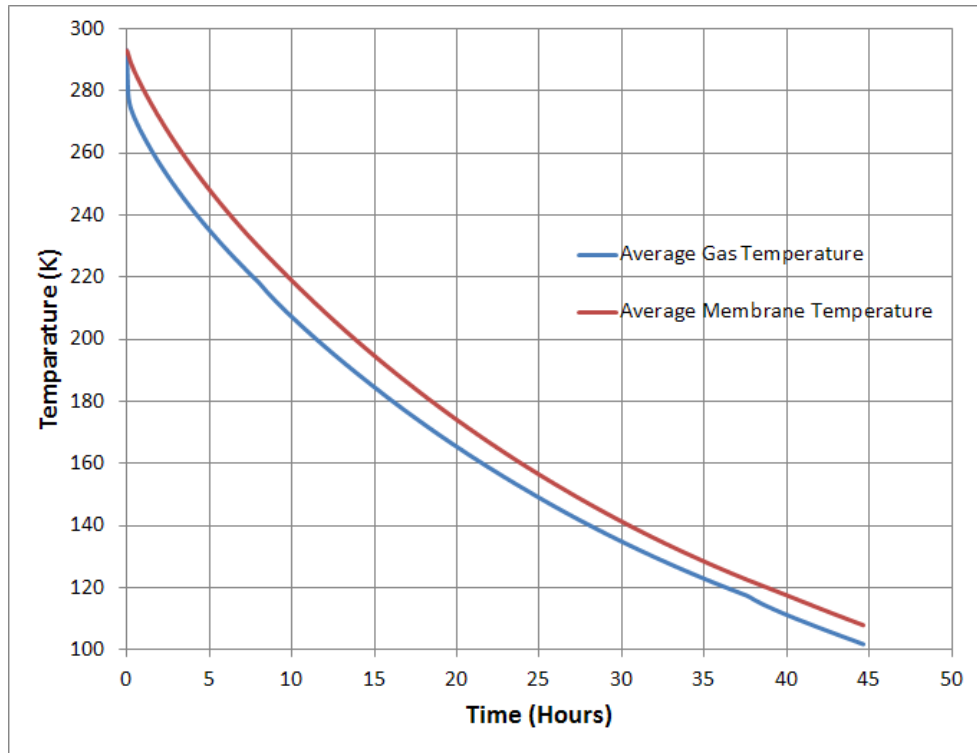


Figure 6: Average temperature of gas space and membrane.

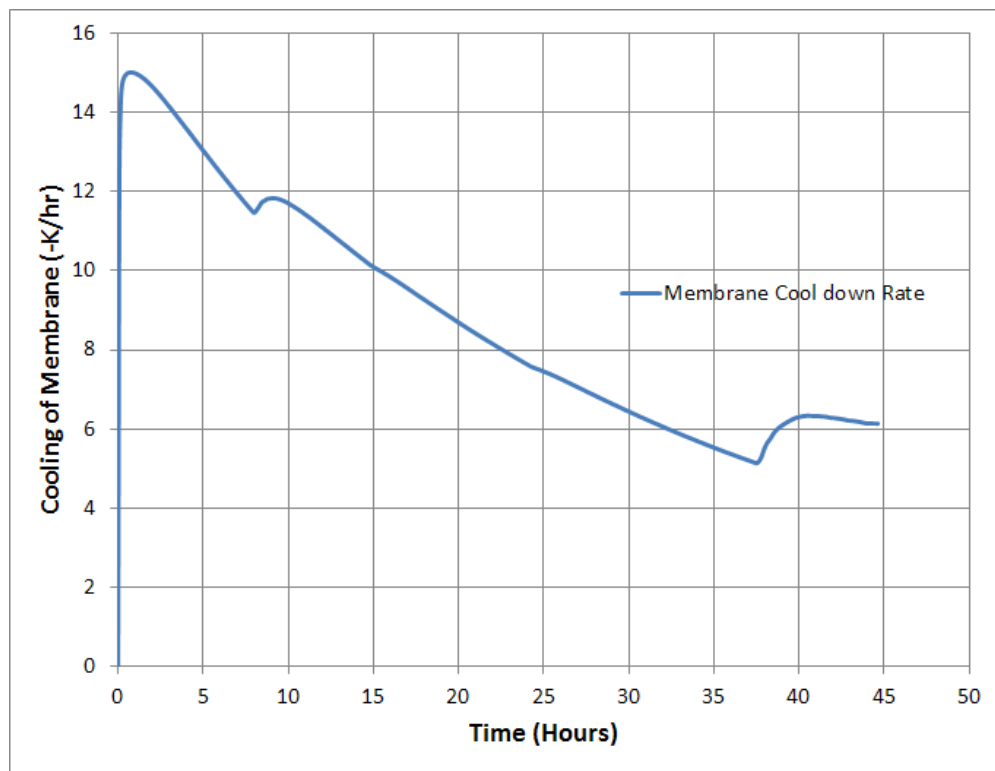


Figure 7: Cooling rate of the membrane.

Numerical Model and Convergence:

Turbulence Model: Shear Stress Transport

Energy Model: Thermal energy (high velocity gas kinetic energy subtracted from cooling power to account for viscous dissipation and avoid using total energy model)

Transient Scheme: Second order - backward Euler

Advection Scheme: High Resolution

Turbulence numeric: High Resolution

Transient time steps: Convergence based adaptive time stepping (max 5 seconds)

Convergence for momentum/mass, energy, and turbulence are shown in Figure 8a, b, c; numerical grid is shown in Figure 9.

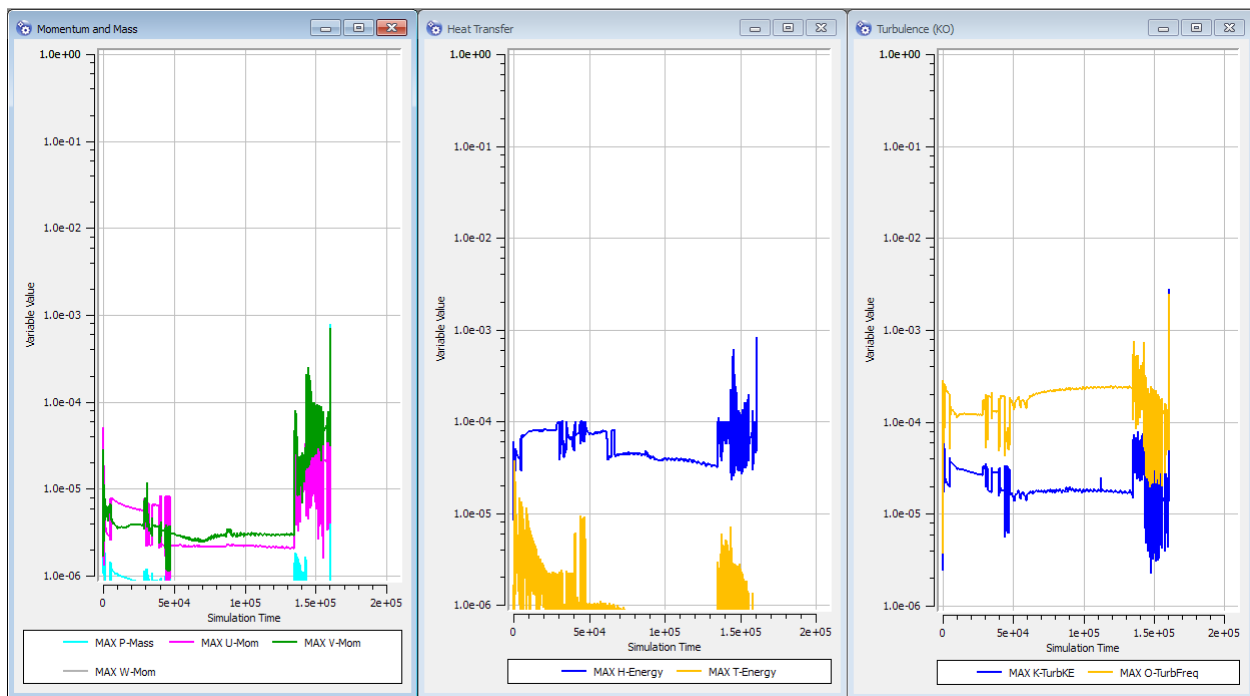


Figure 8: Convergence for momentum/mass, energy, and turbulence; note MAX residuals not RMS.

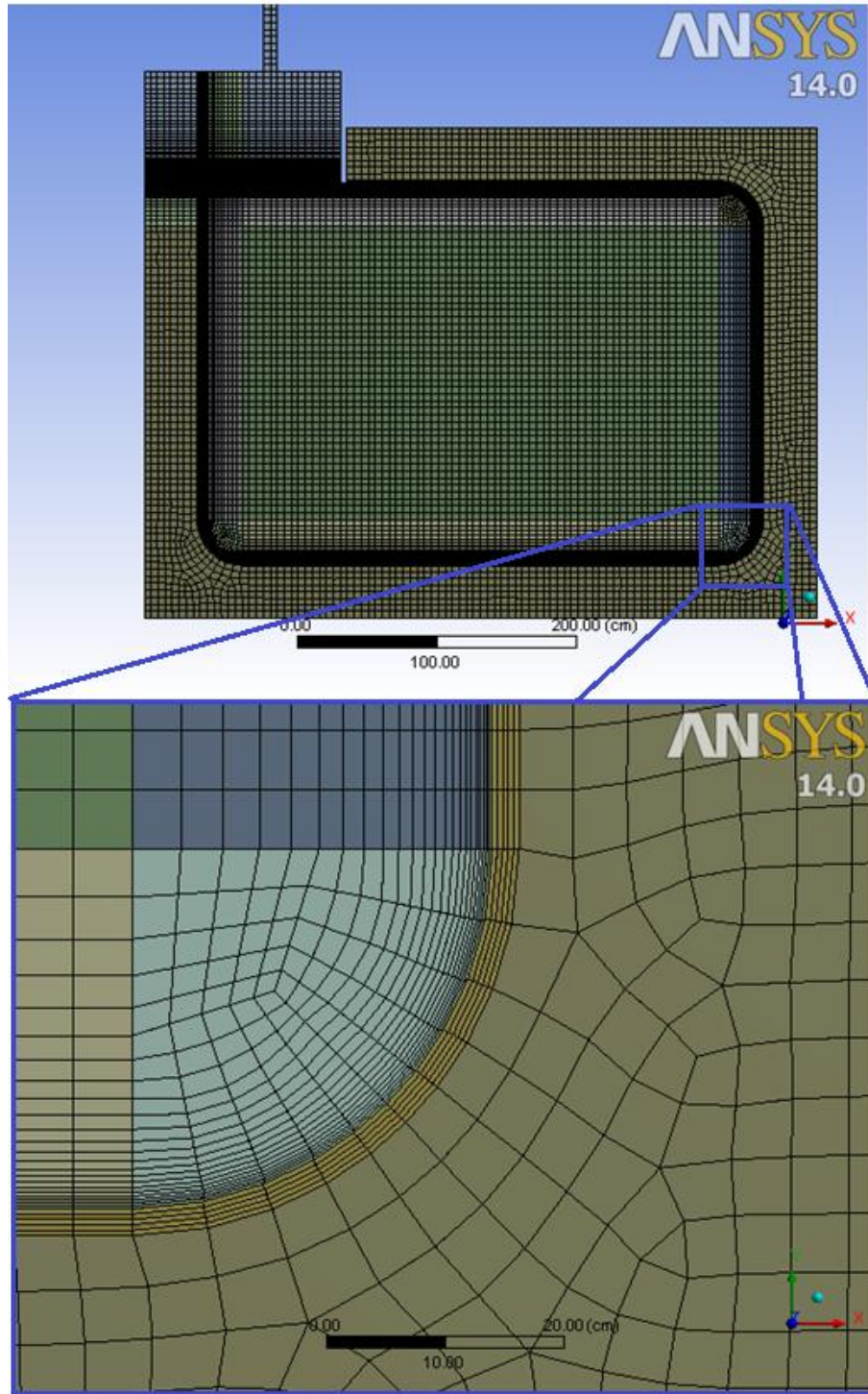


Figure 9: Numerical grid for all domains. (close-up of boundary layer and interface).

APPENDIX - A

Calculations and Model Setup

MATERIAL PROPERTIES

Insulation Thermal properties

$$\rho_{\text{ins}} := 62 \frac{\text{kg}}{\text{m}^3} \quad k_{\text{InsAvgTemp}} := 0.0196 \frac{\text{W}}{\text{m} \cdot \text{K}} \quad \text{Linear formula for conductivity WRT temperature}$$

$$k_{\text{InsAmb}} := 0.027 \frac{\text{W}}{\text{m} \cdot \text{K}} \quad k_{\text{Ins}}(\text{Tm}) := \left(7.00426 \cdot 10^{-5} \cdot \text{Tm} + 0.00625886 \right) \frac{\text{W}}{\text{m} \cdot \text{K}}$$

Specific Heat WRT Temperature (from NIST Cryogenic database)

$$\begin{pmatrix} a \\ b \\ c \\ d \\ e \\ f \\ g \\ h \\ i \end{pmatrix} := \begin{pmatrix} 89.69 \\ -269.32 \\ 333.276 \\ -214.635 \\ 76.2052 \\ -14.1137 \\ 1.061 \\ 0 \\ 0 \end{pmatrix}$$

$$c_{p\text{Ins}}(\text{Tm}) := 10^{a+b \cdot (\log(\text{Tm})) + c \cdot (\log(\text{Tm}))^2 + d \cdot (\log(\text{Tm}))^3 + e \cdot (\log(\text{Tm}))^4 + f \cdot (\log(\text{Tm}))^5 + g \cdot (\log(\text{Tm}))^6 + h \cdot (\log(\text{Tm}))^7 + i \cdot (\log(\text{Tm}))^8} \cdot \frac{\text{J}}{\text{kg} \cdot \text{K}}$$

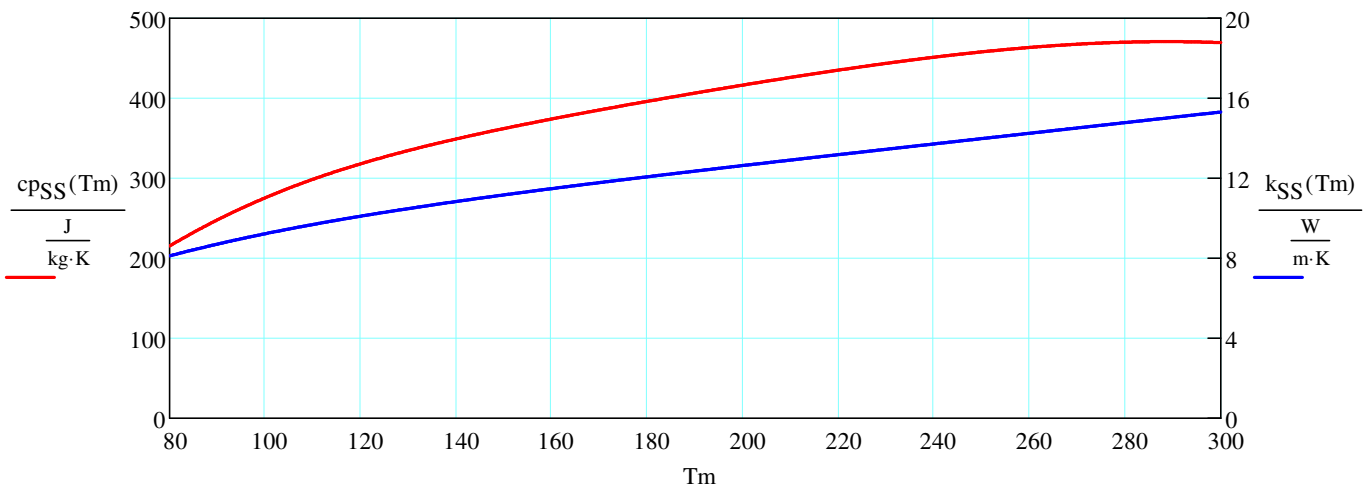
Stainless Steel 304 - Properties WRT Temperature (from NIST Cryogenic database)

$$\begin{pmatrix} a \\ b \\ c \\ d \\ e \\ f \\ g \\ h \\ i \end{pmatrix} := \begin{pmatrix} -1.4087 \\ 1.3982 \\ 0.2543 \\ -0.626 \\ 0.2334 \\ 0.4256 \\ -0.4658 \\ 0.165 \\ -0.0199 \end{pmatrix} \quad \rho_{\text{SS}} := 7854 \frac{\text{kg}}{\text{m}^3}$$

$$k_{\text{SS}}(\text{Tm}) := 10^{\left[a+b \cdot (\log(\text{Tm})) + c \cdot (\log(\text{Tm}))^2 + d \cdot (\log(\text{Tm}))^3 + e \cdot (\log(\text{Tm}))^4 + f \cdot (\log(\text{Tm}))^5 + g \cdot (\log(\text{Tm}))^6 + h \cdot (\log(\text{Tm}))^7 + i \cdot (\log(\text{Tm}))^8 \right]} \cdot \frac{\text{W}}{\text{m} \cdot \text{K}}$$

$$\begin{pmatrix} a \\ b \\ c \\ d \\ e \\ f \\ g \\ h \\ i \end{pmatrix} := \begin{pmatrix} 22.0061 \\ -127.5528 \\ 303.647 \\ -381.0098 \\ 274.0328 \\ -112.9212 \\ 24.7593 \\ -2.239153 \\ 0 \end{pmatrix}$$

$$cp_{SS}(T_m) := 10^{a+b \cdot (\log(T_m)) + c \cdot (\log(T_m))^2 + d \cdot (\log(T_m))^3 + e \cdot (\log(T_m))^4 + f \cdot (\log(T_m))^5 + g \cdot (\log(T_m))^6 + h \cdot (\log(T_m))^7 + i \cdot (\log(T_m))^8} \cdot \frac{J}{kg \cdot K}$$



Plywood properties at ambient temperature / thickness

$$\rho_{\text{plywood}} := 600 \frac{kg}{m^3} \quad k_{\text{plywood}} := 0.174 \frac{W}{m \cdot K} \quad t_{\text{plywood}} := 12mm$$

Fire board properties at ambient temperature / thickness

<http://www.tlimpex.com/Calciumsilicate.html>

$$\rho_{\text{fireboard}} := 600 \frac{kg}{m^3} \quad k_{\text{fireboard}} := 0.099 \frac{W}{m \cdot K} \quad t_{\text{fireboard}} := 10mm$$

Assume the Plywood and Fire board thermal properties behave the same way as insulation WRT Temperature, take ambient ratio and apply multiplier for curve fit.

Plywood Properties WRT Temperature

$$c_{p\text{Plywood}}(T_m) := 1.1 \cdot c_{p\text{Ins}}(T_m)$$

$$k_{\text{Plywood}}(T_m) := 6.488 k_{\text{Ins}}(T_m)$$

Fire board Properties WRT Temperature

$$c_{p\text{Fireboard}}(T_m) := 0.629 \cdot c_{p\text{Ins}}(T_m)$$

$$k_{\text{Fireboard}}(T_m) := 3.697 k_{\text{Ins}}(T_m)$$

Form an equivalent material for the Fire board and Plywood since they have nearly identical thermal diffusivity and will behave the same in a transient thermal scenario.

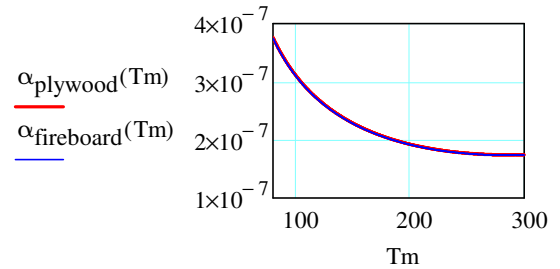
$$t_{\text{model}} := 22.5\text{mm} \quad \alpha_{\text{fireboard}}(T_m) := \frac{k_{\text{Fireboard}}(T_m)}{\rho_{\text{fireboard}} \cdot c_{p\text{Fireboard}}(T_m)}$$

$$\alpha_{\text{plywood}}(T_m) := \frac{k_{\text{Plywood}}(T_m)}{\rho_{\text{plywood}} \cdot c_{p\text{Plywood}}(T_m)}$$

Density

$$W_{\text{membrane}} := t_{\text{plywood}} \cdot \rho_{\text{plywood}} + t_{\text{fireboard}} \cdot \rho_{\text{fireboard}}$$

$$\rho_{\text{eq}} := \frac{W_{\text{membrane}}}{t_{\text{model}}} = 586.667 \frac{\text{kg}}{\text{m}^3}$$



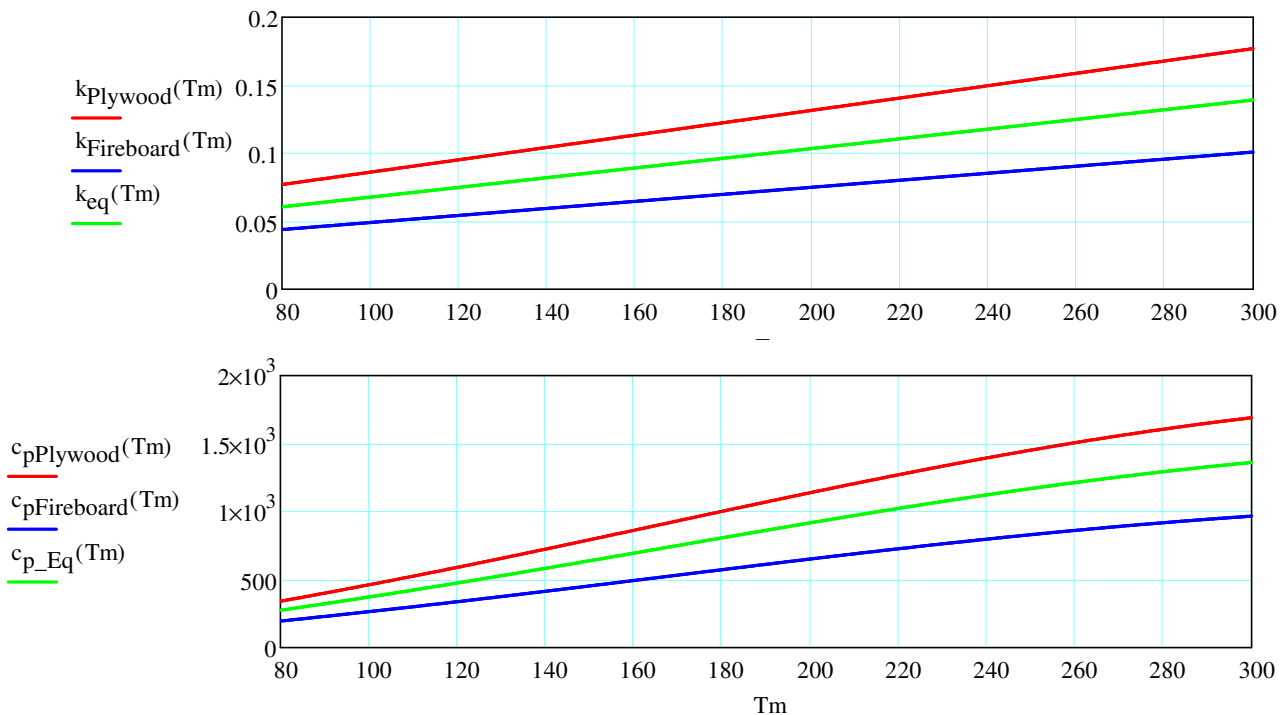
Thermal Mass / Heat Capacity

$$Q_{\text{membrane}}(T_m) := c_{p\text{Plywood}}(T_m) \cdot t_{\text{plywood}} \cdot \rho_{\text{plywood}} + c_{p\text{Fireboard}}(T_m) \cdot t_{\text{fireboard}} \cdot \rho_{\text{fireboard}}$$

$$c_{p_Eq}(T_m) := \frac{Q_{\text{membrane}}(T_m)}{W_{\text{membrane}}}$$

Thermal Conductivity

$$k_{\text{eq}}(T_m) := \frac{t_{\text{fireboard}} \cdot k_{\text{Fireboard}}(T_m) + t_{\text{plywood}} \cdot k_{\text{Plywood}}(T_m)}{t_{\text{model}}}$$



Argon Gas Properties WRT Temperature

$$h_{Ar}(T_{mp}) := \text{interp}\left(\text{regress}\left(M_T, h_T, 3\right), M_T, h_T, T_{mp}\right) \cdot \frac{\text{kJ}}{\text{kg}}$$

$$k_{Ar}(T_{mp}) := \text{interp}\left(\text{regress}\left(M_T, k_T, 2\right), M_T, k_T, T_{mp}\right) \cdot \frac{\text{W}}{\text{m} \cdot \text{K}}$$

$$cp_{Ar}(T_{mp}) := \text{interp}\left(\text{regress}\left(M_T, cp_T, 7\right), M_T, cp_T, T_{mp}\right) \cdot \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$\mu_{Ar}(T_{mp}) := \text{interp}\left(\text{regress}\left(M_T, \mu_T, 2\right), M_T, \mu_T, T_{mp}\right) \cdot \mu\text{Pa} \cdot \text{s}$$

$$\rho_{Ar}(T_{mp}) := 574.5252575 \cdot T_{mp}^{-1.022310295} \frac{\text{kg}}{\text{m}^3}$$

$$\beta_{Ar}(T_{mp}) := \text{interp}\left(\text{regress}\left(M_T, \beta_T, 3\right), M_T, \beta_T, T_{mp}\right) \cdot \frac{1}{\text{K}}$$

$$\text{Temp}(h) := \text{interp}\left(\text{regress}\left(h_T, M_T, 6\right), h_T, M_T, h\right) \text{K}$$

$$\text{Pr}(T_{mp}) := \frac{\mu_{Ar}(T_{mp}) \cdot cp_{Ar}(T_{mp})}{k_{Ar}(T_{mp})} \quad \alpha_{Ar}(T_{mp}) := \frac{k_{Ar}(T_{mp})}{\left(cp_{Ar}(T_{mp}) \cdot \rho_{Ar}(T_{mp})\right)}$$

Modeling the liquid/gas sprayers

Modeling of LAr sprayer will be achieved by:

- 1.) Energy source - From LAr evaporation into gas
- 2.) Continuity source - The mass of vaporized LAr and argon gas added to the volume
- 3.) Momentum source - From the sprayers gas coming out at high velocity

****Calculations are done (PER NOZZLE)**

$$\rho_{\text{LAr}} := 1392.9 \frac{\text{kg}}{\text{m}^3} \quad \rho_{\text{GAr}}(\text{Tmp}) := 574.5252575 \cdot \text{Tmp}^{-1.022310295} \frac{\text{kg}}{\text{m}^3}$$

Liquid Argon

Total Ambient Argon Gas

$$\text{liquid}_{\text{spray}} := 1.3 \text{gph} \cdot (133\%) \cdot (125\%) = 2.161 \cdot \text{gph}$$

$$\text{gas}_{\text{spray}} := 1.2 \text{SCFM} \cdot (166\%) \cdot (125\%) = 2.49 \cdot \text{SCFM}$$

Percent of gas input from additional straight gas nozzles

$$\text{Percent}_{\text{GasStraight}} := 50\%$$

$$h_{\text{fg}} := 160.83 \frac{\text{kJ}}{\text{kg}}$$

Continuity / mass entering system

We will use one sprayer which sprays:

$$\text{liquid}_{\text{mass}} := \text{liquid}_{\text{spray}} \cdot \rho_{\text{LAr}} = 3.165 \frac{\text{gm}}{\text{sec}}$$

Pressure during cool down and STD

$$P_{\text{cryostat}} := 15.33 \text{psi} \quad \rho_{\text{ArSTD}} := 1.6875 \frac{\text{kg}}{\text{m}^3}$$

$$\text{gas}_{\text{mass}} := \text{gas}_{\text{spray}} \cdot \rho_{\text{ArSTD}} = 1.983 \frac{\text{gm}}{\text{sec}}$$

At saturation Temperature

$$\text{Continuity} := \text{liquid}_{\text{mass}} + \text{gas}_{\text{mass}} = 5.149 \frac{\text{gm}}{\text{sec}}$$

Momentum entering system

Nozzle Dimensions

$$d_{\text{Gsprayer}} := 0.035 \text{in} \quad A_{\text{Gsprayer}} := \frac{\pi}{4} \cdot d_{\text{Gsprayer}}^2 \cdot 2$$

$$d_{\text{Lsprayer}} := 0.025 \text{in} \quad A_{\text{Lsprayer}} := \frac{\pi}{4} \cdot d_{\text{Lsprayer}}^2$$

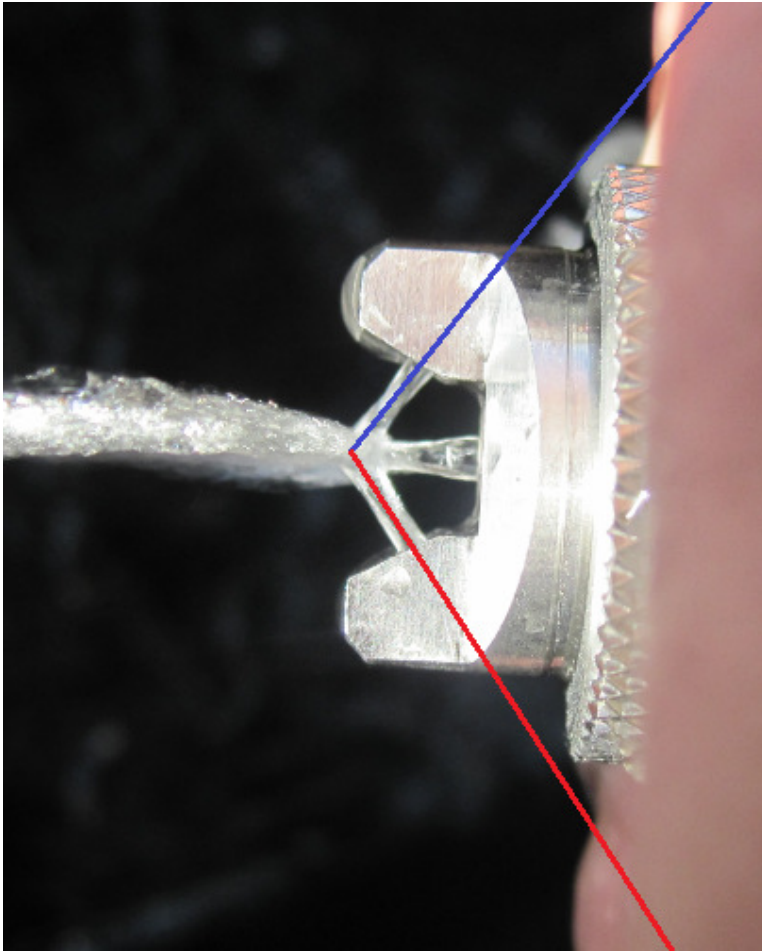
$$V_{\text{GAr}} := \frac{\text{gas}_{\text{mass}}}{A_{\text{Gsprayer}} \cdot \rho_{\text{GAr}}(293)} = 925 \frac{\text{m}}{\text{s}}$$

$$V_{\text{GAr}} := 343 \frac{\text{m}}{\text{s}}$$

We will use sonic velocity as this is too high, meaning we will have choked sonic flow at a higher pressure in the nozzle.

Gas nozzles do not spray straight, we must reduce the momentum accordingly

$$\text{MomentumGas} := V_{\text{GAr}} \cdot \text{gas}_{\text{mass}} = 0.68 \cdot \frac{\text{N} \cdot \text{s}}{\text{s}}$$



Count pixels to determine angles

$$\text{angle}_{\text{Top}} := \text{atan}\left(\frac{226}{284}\right) = 38.512 \cdot \text{deg}$$

$$\text{angle}_{\text{Bot}} := \text{atan}\left(\frac{196}{304}\right) = 32.811 \cdot \text{deg}$$

$$\text{outletAngle} := \frac{1}{2}(\text{angle}_{\text{Top}} + \text{angle}_{\text{Bot}}) = 35.662 \cdot \text{deg}$$

$$\text{M}_{\text{Reduction}} := \sin(\text{outletAngle}) = 58.3 \cdot \%$$

$$\text{M}_{\text{GasAngled}} := \text{MomentumGas} \cdot \text{M}_{\text{Reduction}} \cdot (1 - \text{Percent}_{\text{GasStraight}}) = 0.198 \cdot \frac{\text{N} \cdot \text{s}}{\text{s}}$$

$$\text{M}_{\text{GasStraight}} := \text{MomentumGas} \cdot (\text{Percent}_{\text{GasStraight}}) = 0.34 \cdot \frac{\text{N} \cdot \text{s}}{\text{s}}$$

$$\text{M}_{\text{Gas}} := \text{M}_{\text{GasAngled}} + \text{M}_{\text{GasStraight}} = 0.538 \cdot \frac{\text{N} \cdot \text{s}}{\text{s}}$$

Liquid Argon Momentum

$$V_{\text{LAr}} := \frac{\text{liquid}_{\text{spray}}}{A_{\text{Lsprayer}}} = 7.2 \frac{\text{m}}{\text{s}} \quad \text{M}_{\text{Liq}} := V_{\text{LAr}} \cdot \text{liquid}_{\text{spray}} \cdot \rho_{\text{LAr}} = 0.023 \cdot \frac{\text{N} \cdot \text{s}}{\text{s}}$$

Total Momentum

$$\text{Momentum} := \text{M}_{\text{Gas}} + \text{M}_{\text{Liq}} = 0.561 \cdot \frac{\text{N} \cdot \text{s}}{\text{s}}$$

Energy entering system (additional cooling from vaporizing LAr)

How much argon Liquid spray will be vaporized by the included gas spray, and how much energy will come from surrounding argon already in the cryostat?

mass and energy balance to find how much is vaporized by included gas

$$\text{gas}_{\text{mass}} \cdot \int_{87.704}^{293} c_{p\text{Ar}}(\text{Tmp}) \, d\text{Tmp} \cdot \text{K} = \text{mass}_{\text{liqEvap}} \cdot h_{fg}$$

Cooling from Cold Gas (from 293K)

$$\text{mass}_{\text{liqEvap}} := \text{Find}(\text{mass}_{\text{liqEvap}}) = 1.338 \cdot \frac{\text{gm}}{\text{sec}}$$

$$\text{gas}_{\text{mass}} \cdot \int_{87.704}^{293} c_{p\text{Ar}}(\text{Tmp}) \, d\text{Tmp} \cdot \text{K} = 215.113 \cdot \text{W}$$

Remaining liquid spray

$$\text{LiqNotVaporized} := \text{liquid}_{\text{mass}} - \text{mass}_{\text{liqEvap}} = 1.828 \cdot \frac{\text{gm}}{\text{sec}}$$

$$\text{Energy}_{\text{Liq}} := \text{LiqNotVaporized} \cdot (h_{fg}) = 293.987 \, \text{W}$$

Kinetic Energy of the high velocity gas spray

Remaining Cooling Energy of fine liquid mist

$$\text{Energy}_{\text{Spray}} := \frac{1}{2} \cdot \text{gas}_{\text{mass}} \cdot V_{\text{GAr}}^2 = 116.653 \, \text{W}$$

$$\text{Energy} := -(\text{Energy}_{\text{Liq}} - \text{Energy}_{\text{Spray}}) = -177.334 \, \text{W}$$

Apply These Values to a "Spray Volume" from the nozzles flow pattern

Spray Volume

$$H_{\text{spray}} := 15\text{cm} \quad L_{\text{spray}} := 120\text{cm} \quad D_{\text{cryostat}} := 270\text{cm}$$

$$\text{SprayVolume} := H_{\text{spray}} \cdot L_{\text{spray}} \cdot D_{\text{cryostat}} = 486 \, \text{L}$$

Volumetric Source Values (input into CFD model - PER SPRAYER)

$$\text{Momentum}_{\text{Source}} := \frac{\text{Momentum}}{\text{SprayVolume}} = 1.1545 \cdot \frac{\text{kg}}{\text{m}^2 \cdot \text{s}}$$

$$\text{Continuity}_{\text{Source}} := \frac{\text{Continuity}}{\text{SprayVolume}} = 0.0105937 \cdot \frac{\text{kg}}{\text{m}^3 \cdot \text{s}}$$

$$\text{Energy}_{\text{Source}} := \frac{\text{Energy}}{\text{SprayVolume}} = -365 \cdot \frac{\text{W}}{\text{m}^3}$$

Calculate/Estimate cooling power/time

$$\text{numSprayers} := 7$$

$$\text{Total}_{\text{Liquid}} := \text{liquid}_{\text{spray}} \cdot \text{numSprayers} \cdot \rho_{\text{LAr}} = 22.158 \cdot \frac{\text{gm}}{\text{sec}}$$

$$\text{Total}_{\text{Gas}} := \text{gas}_{\text{spray}} \cdot \text{numSprayers} \cdot \rho_{\text{ArSTD}} = 13.881 \cdot \frac{\text{gm}}{\text{sec}}$$

$$\text{Total}_{\text{Continuity}} := \text{Continuity} \cdot \text{numSprayers} = 36.04 \cdot \frac{\text{gm}}{\text{sec}} \quad (\text{gas at } 87.704\text{K})$$

$$\text{Total}_{\text{Energy}} := \text{Energy} \cdot \text{numSprayers} = -1241 \text{ W} \quad (\text{additional cooling from liquid vaporization})$$

$$\text{Total}_{\text{Momentum}} := \text{Momentum} \cdot \text{numSprayers} = 3.928 \cdot \frac{\text{N} \cdot \text{s}}{\text{s}}$$

$$\text{STD}_{\text{ArFlow}} := \frac{\text{Total}_{\text{Continuity}}}{\rho_{\text{ArSTD}}} = 45.253 \cdot \text{SCFM}$$

Cooling Power WRT Gas Temperature

$$\text{CoolingPower}(\text{Tmp}) := \left[\text{Continuity} \cdot \left(h_{\text{Ar}}(\text{Tmp}) - h_{\text{Ar}}(87.704) \right) - \text{Energy} \right] \cdot \text{numSprayers}$$

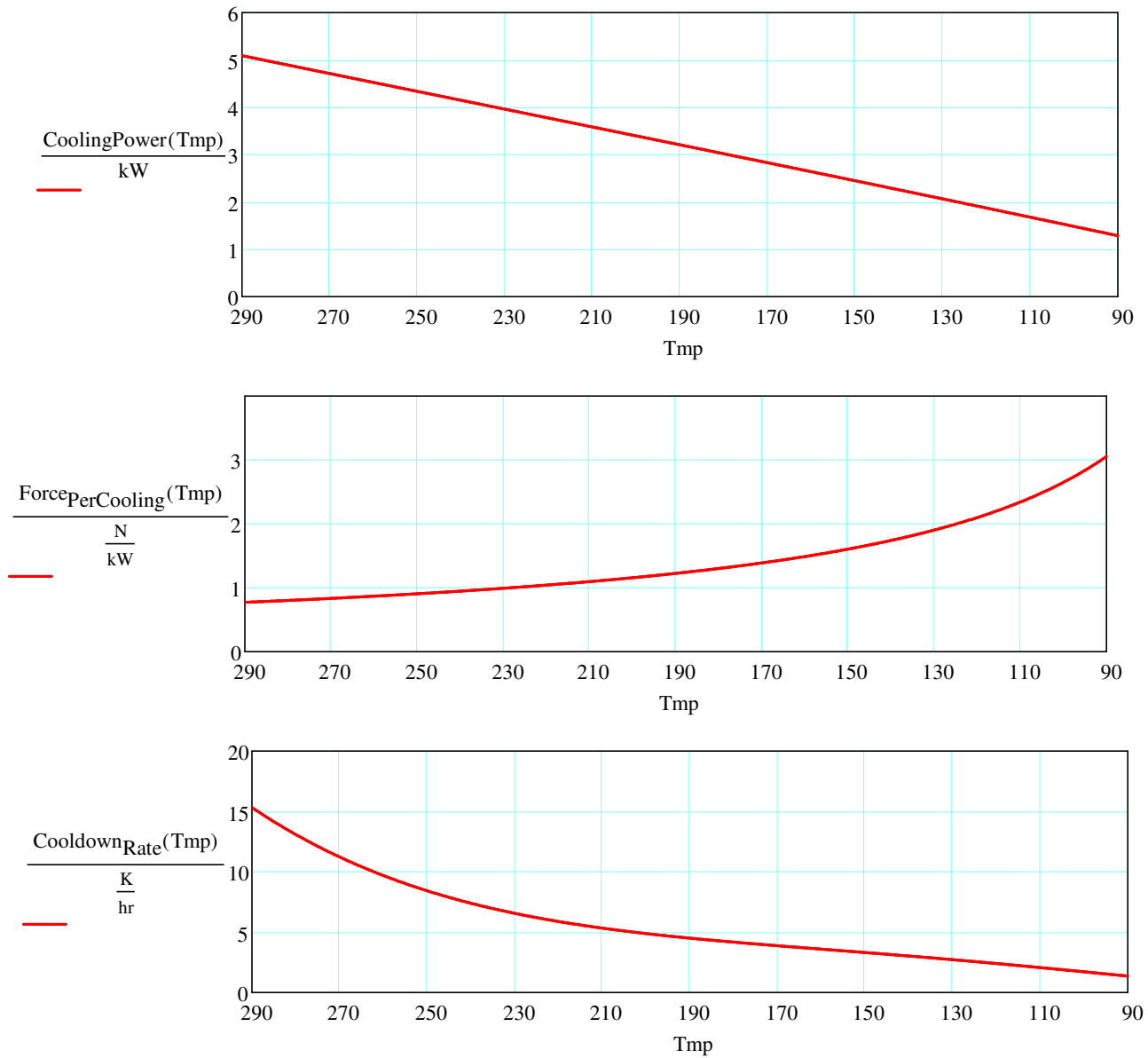
Momentum to Cooling Ratio

$$\text{Force}_{\text{PerCooling}}(\text{Tmp}) := \frac{\text{Momentum} \cdot \text{numSprayers}}{\text{CoolingPower}(\text{Tmp})} \quad \text{Force}_{\text{PerCooling}}(293) = 0.763 \cdot \frac{\text{N}}{\text{kW}}$$

Estimated Cool down Rate from Several CFD analyses (SS Membrane Temp)

$$\text{CooldownRate}(\text{Tmp}) := \text{CoolingPower}(\text{Tmp}) \cdot \left(7.10864 \cdot 10^{-7} \cdot \text{Tmp}^3 - 0.000342304 \cdot \text{Tmp}^2 + 0.055746223 \cdot \text{Tmp} - 1.707049 \right) \frac{\text{K}}{\text{hr} \cdot \text{kW}}$$

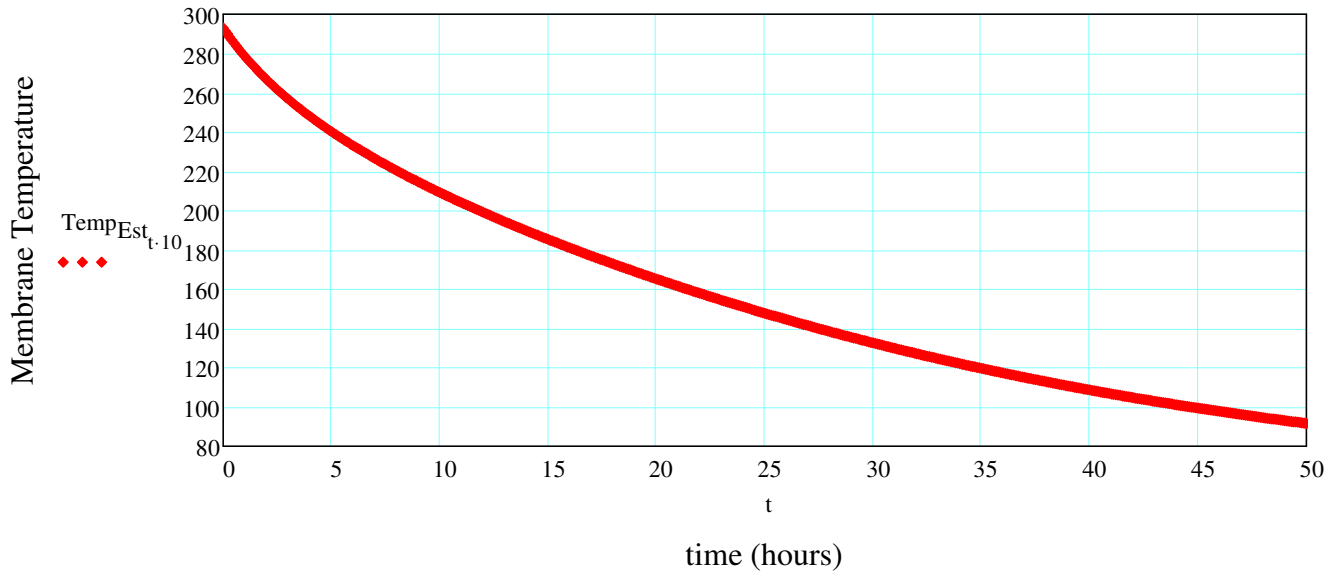
Graphical Results WRT Gas space Temperature



Transient Temperature Estimate

timesteps := 500 timePeriod := $\frac{1}{10}$ · hr

Temp_{Est} := $\left\{ \begin{array}{l} \text{Temp}_{\text{Est}_0} \leftarrow 293\text{K} \\ \text{for } i \in 1.. \text{timesteps} \\ \quad \text{Temp}_{\text{Est}_i} \leftarrow \text{Temp}_{\text{Est}_{i-1}} - \text{CooldownRate}\left(\frac{\text{Temp}_{\text{Est}_{i-1}}}{\text{K}}\right) \cdot \text{timePeriod} \\ \text{return Temp}_{\text{Est}} \end{array} \right.$



Determine Flow Pattern

Number of sprayers changes Reynolds and Grashof numbers:

$$\text{LengthScale_Re} := 16\text{m}$$

$$\text{LengthScale_Gr} := 16\text{m}$$

Temperature and Velocity Scales Estimated from several cool down CFD analyses

$$\Delta T_{\text{scale}}(\text{Tmp}) := \text{CoolingPower}(\text{Tmp}) \cdot (3.3855574 - 0.0001027881 \cdot \text{Tmp}) \cdot 0.8 \frac{\text{K}}{\text{kW}}$$

$$T_M := \frac{\text{Momentum}}{N} \cdot \text{numSprayers} = 3.928$$

$$\text{Velocity}_{\text{scale}}(\text{Tmp}) := \left(0.385 \frac{\text{m}}{\text{sec}} \right) \cdot \left[-0.110339627 \cdot (T_M)^2 + 1.28361 \cdot T_M + 0.65789 \right] \cdot (0.003470419 \cdot \text{Tmp} + 1.369)$$

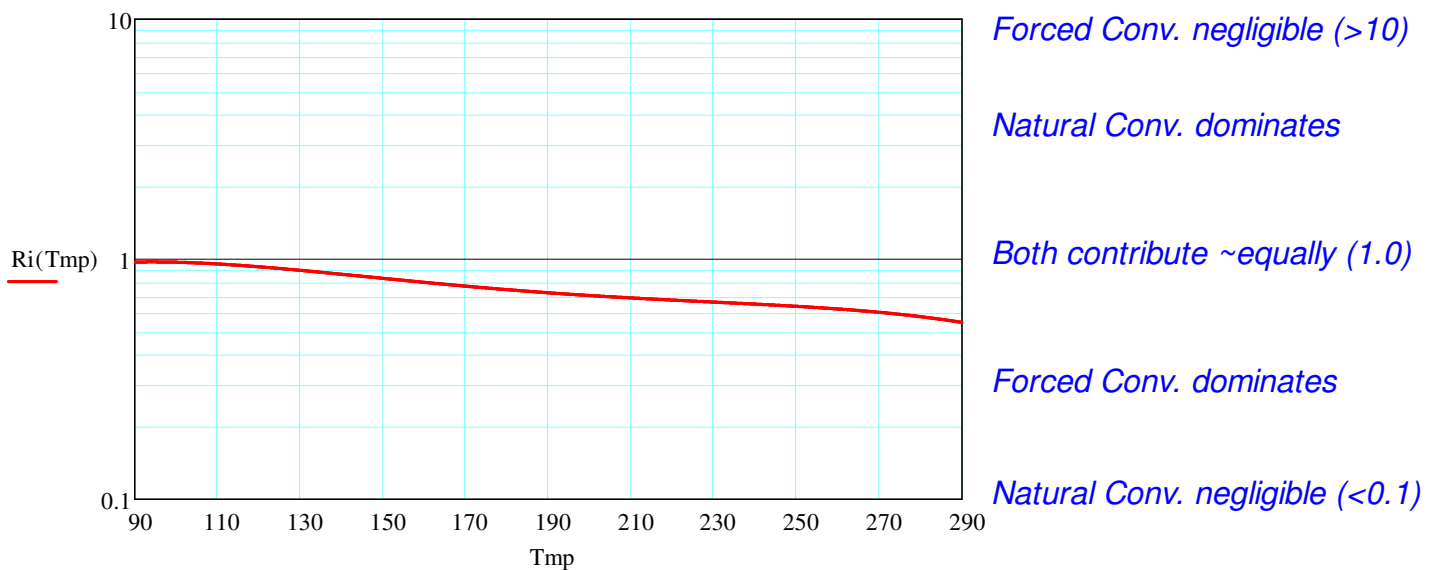
Grashof and Reynolds numbers

$$\text{Gr}(\text{Tmp}) := \frac{g \cdot \beta_{\text{Ar}}(\text{Tmp}) \cdot \Delta T_{\text{scale}}(\text{Tmp}) \cdot \text{LengthScale_Gr}^3}{\left(\frac{\mu_{\text{Ar}}(\text{Tmp})}{\rho_{\text{Ar}}(\text{Tmp})} \right)^2} \quad \text{Re}(\text{Tmp}) := \frac{\rho_{\text{Ar}}(\text{Tmp}) \cdot \text{Velocity}_{\text{scale}}(\text{Tmp}) \cdot \text{LengthScale_Re}}{\mu_{\text{Ar}}(\text{Tmp})}$$

Richardson numbers describe whether forced or natural convection will dominate.

$$\text{Ri}(\text{Tmp}) := \frac{\text{Gr}(\text{Tmp})}{\text{Re}(\text{Tmp})^2}$$

Both forced and natural convection play a role in transport of heat energy, though as we add more momentum, or more sprayers, forced convection dominates, meaning much less thermal stratification, and more homogeneous temperature field in the gas space as well as temperature of the membrane.



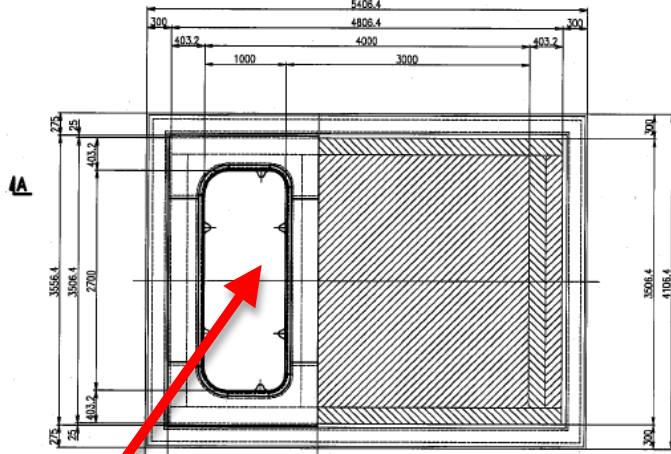
This specification of cooling and momentum ensures we will have a forced convection dominated flow, homogeneous temperature field, and a steady flow pattern.

Notes/Thoughts on flow pattern characteristics / parameters:

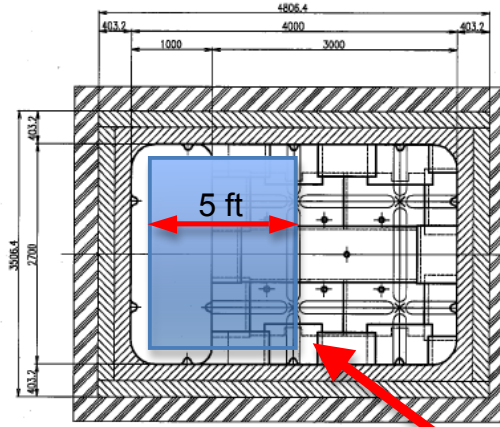
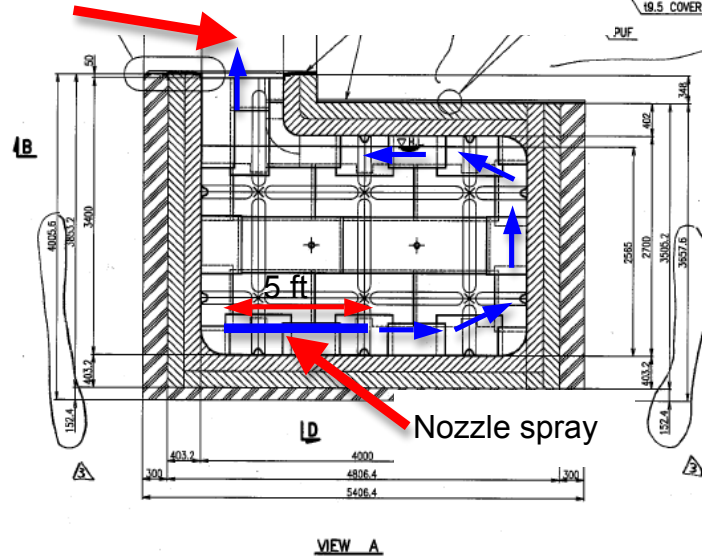
- 1.) Equal percentage increase in both momentum and cooling (liquid and gas) will push the fluid flow regime more toward the forced convection dominated regime. This means if we increase the ratio of both as the cryostat cools we can accelerate cooling, as well as decrease Richardson.
- 2.) An equal percentage increase in momentum and cooling (liquid and gas) will also act to better homogenize the temperature field, even when influenced by buoyancy.
- 3.) It is believed any additional mass in the membrane (more corrugations, backing strips, bolts, welds, etc.) will not greatly influence the flow pattern or temperature distribution, but only the actual cooldown time.
- 3.) 2D model **may** be conservative as to when natural convection influences flow, as increased heat flux at the higher density left wall (remember the 2D to 3D conversion) may overpredict the effects of buoyant flow at the interface with the gas. In reality it may be much easier (less momentum required) to keep a forced convection dominated flow.
- 4.) 3D model might be attempted to confirm 2D simplification, though computation resources may be insufficient.

APPENDIX - B

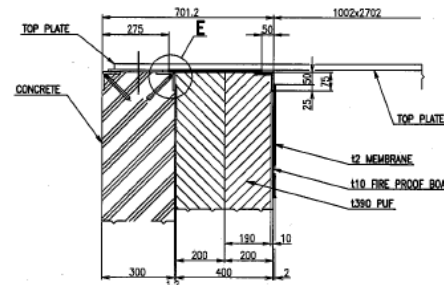
Cryostat and Sprayer Information
(authored by Terry Tope and Mark Adamowski)



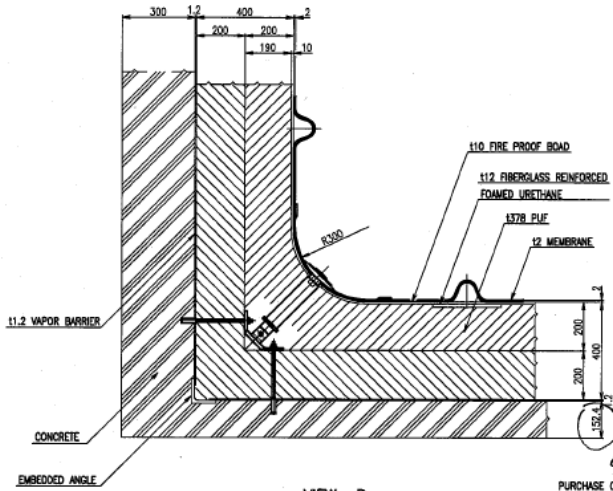
Gas exits from this part of the tank. The exit details can be designed once we understand the flow in the tank. For example a gas withdrawal manifold could extend into the tank.



VIEW B



DETAIL C



VIEW D

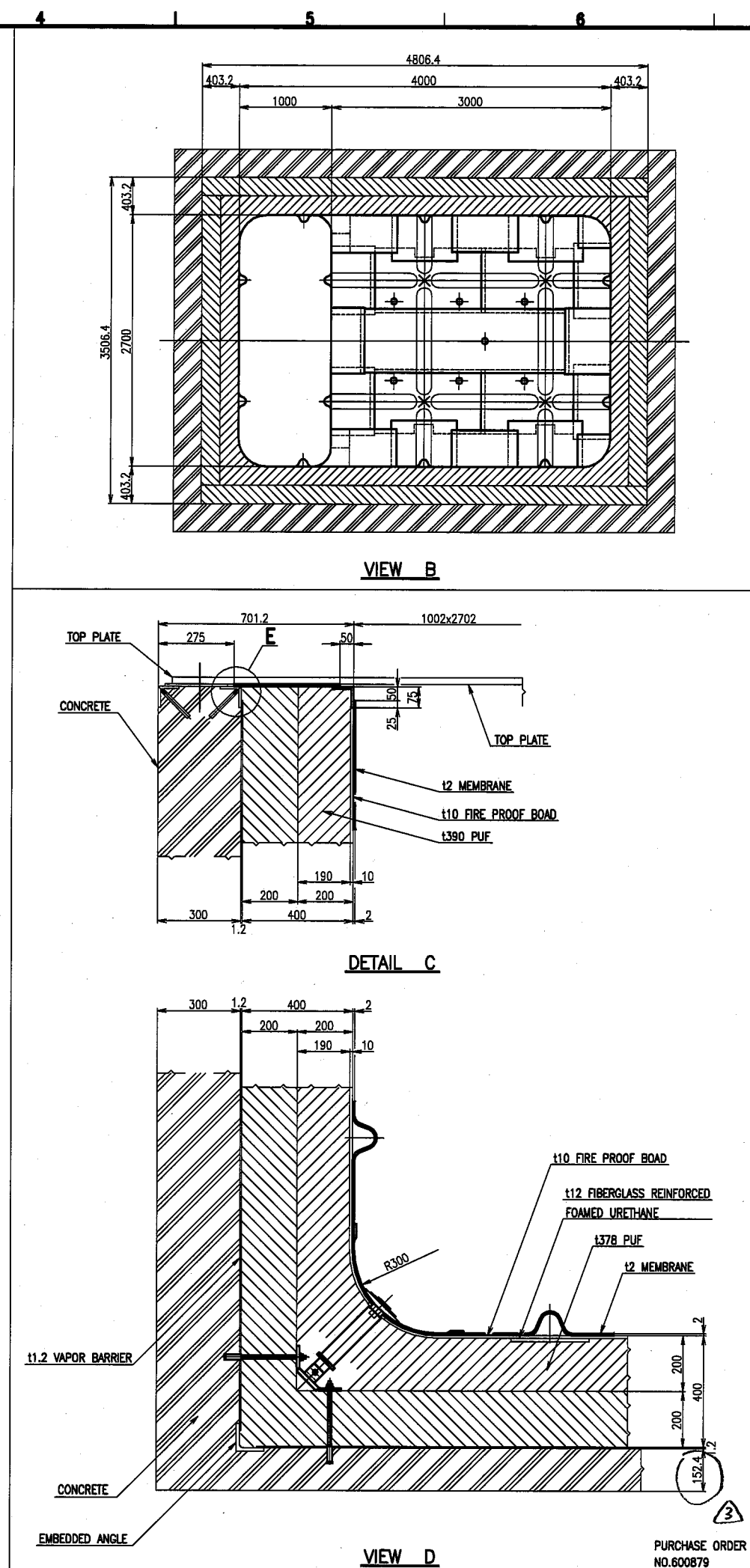
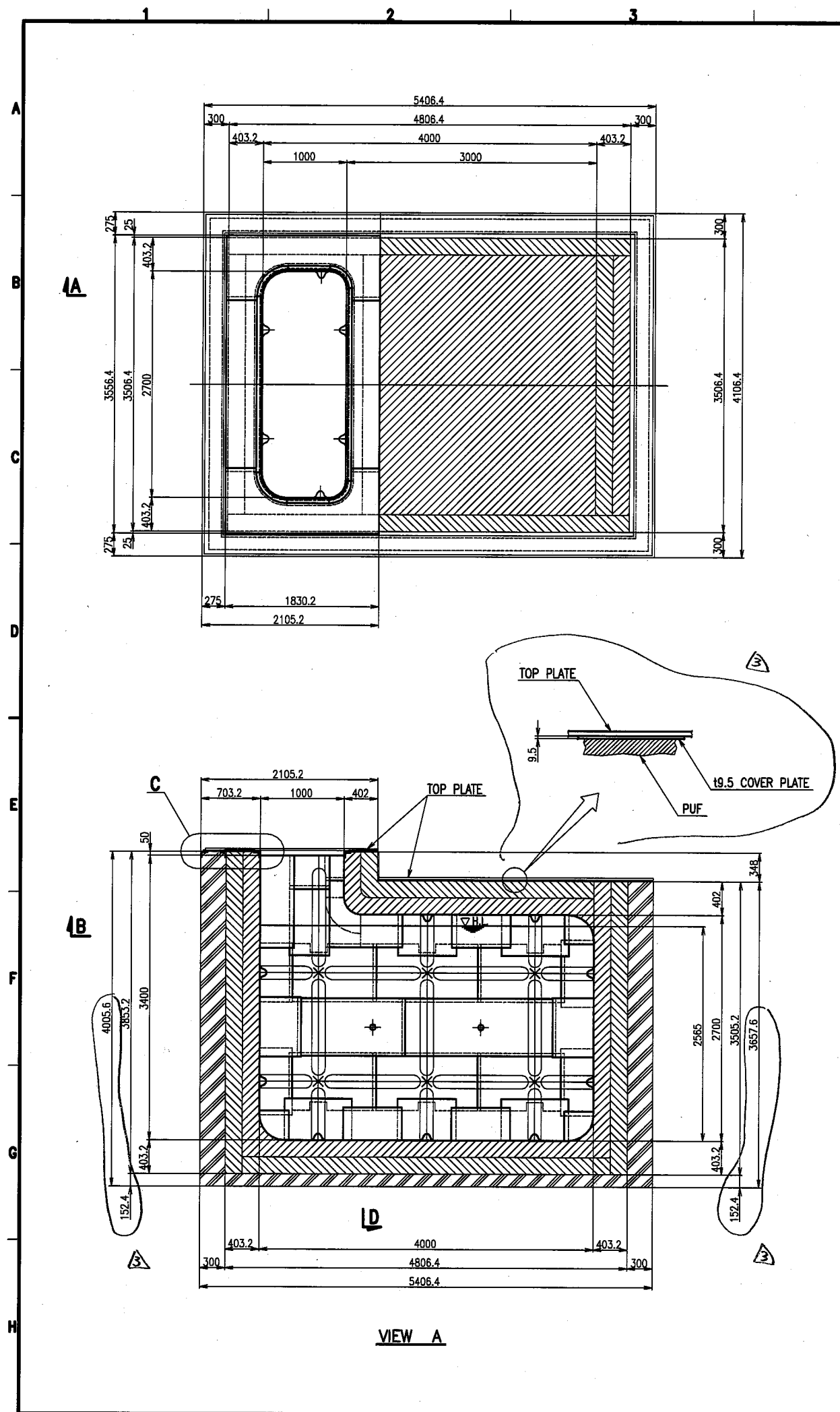
DESIGN DATA	
TANKTYPE	MEMBRANE
CONTENTS	LIQUID ARGON
CAPACITY	28m³
DESIGN TEMPERATURE (MEMBRANE)	MIN 84K (-189°C)
	MAX 339K (66°C)
DESIGN PRESSURE	20.7kPaG
EXTERNAL PRESSURE	0.15kPaG
	in case of no internal pressure
DESIGN DENSITY	1393kg/m³
LIQUID HEIGHT	2565mm
MATERIAL	MEMBRANE 304 STAINLESS STEEL
	INSULATION PUF (POLYURETHANE FOAM)

Spray of gas and liquid droplets from a set of nozzles. The nozzles make a flat spray pattern. Heat input from the tank will vaporize the liquid droplets in the spray. Vaporized liquid results in an equivalent flow of 60 SCFM argon gas (or 17 CFM at flowing conditions of 87 K and atm pressure).

APPROVED ISSUE

NO.	DATE	DESCRIPTION	ISSUED	REVISION	CHECKED	APPROVED
3	14 Feb 12	ISSUED FOR CONSTRUCTION	—	—	—	—
2	22 Dec 11	ISSUED FOR CONSTRUCTION	—	—	—	—
1	14 Nov 11	ISSUED FOR APPROVAL	—	—	—	—
0	21 Aug 11	ISSUED FOR APPROVAL	—	—	—	—
SCALE						
FERMILAB						
LBNE 35TON PROTOTYPE PROJECT						
GENERAL ARRANGEMENT OF MEMBRANE TANK						
TANKEGE G. Basic Engineering Dept. Plants Operations.			JOB NO. 5021-521		DRAWING NO. D4000-6101	
PURCHASE ORDER NO. 800879			REV. 3		TEL. 03-5204-7819	

IHI Corporation



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LIQUID HEIGHT	2565mm
MATERIAL	MEMBRANE 304 STAINLESS STEEL INSULATION PUF (POLYURETHANE FOAM)

DETAIL E

DETAIL C

DETAIL D

APPROVED ISSUE

NO.	DATE	DESCRIPTION	DRAWN	DESIGNED	CHECKED	APPROVED
3	19.Feb.12	ISSUED FOR CONSTRUCTION				E. Komiya
2	22.Dec.11	ISSUED FOR CONSTRUCTION				E. Komiya
1	14.Nov.11	ISSUED FOR APPROVAL				E. Komiya
0	23.Aug.11	ISSUED FOR APPROVAL				E. Komiya

FERMILAB
LBNE 35TON PROTOTYPE PROJECT
GENERAL ARRANGEMENT OF MEMBRANE TANK

Tankage G.
Basic Engineering Dept.
Plants Operations.

JOB NO. 5021-521
DRAWING NO. D4000-6101
REV. 1/3

IHI Corporation